A RESONANT INFRARED PHOTOCONDUCTOR WITH UNIT QUANTUM EFFICIENCY

Jam Farhoomand* and Robert E. McMurray, Jr.
** Orion TechnoScience, Palo Alto, California*
NASA/Ames Research Center, Moffett Field, California

In this presentation we introduce a new concept for an infrared photoconductor and demonstrate that such a detector can, theoretically, exhibit unit quantum efficiency at selected frequencies. The idea is based on establishing a relatively high finesse absorption-cavity internal to the detector element and tuning the front surface reflectivity and the dopant concentration of the detector to achieve improved performance. A theoretical analysis demonstrates this concept and provides the relevant design parameters. This approach offers many other advantages over conventional photoconductors as well as impurity-band-conduction approach. Among those are enhanced photoconductive gain, improved noise performance, and better immunity against ionizing radiation.

Quantum efficiency is perhaps the single most important parameter of an infrared photoconductor . Attempts to improve this parameter have lead the investigators to devise methods of increasing the absorption properties of detectors.

Increasing the dopant concentration is one method which will improve the absorption coefficient but, at the same time, will increase the leakage current. High leakage current and hopping conduction degrades the detector's noise performance. In an impurity-band-conduction (IBC) detector, one tries to overcome this problem by growing a high purity epitaxial layer on the top of the active layer.[1,2,3] An IBC detector, therefore, can theoretically take advantage of a very high dopant concentration with improved NEP because of this blocking epi-layer. Although the IBC concept has been successfully demonstrated for mid-infrared silicon detectors, the technology for far infrared detectors is far from optimum.

Geometrical schemes can also be used to increase the optical length of a detector. One of the most common methods is the utilization of an integrating cavity behind the detector. In another scheme, the detector's exit end is beveled at the proper angle to induce total internal reflection.[4] Although these approaches are easily implemented on a single discrete detector, they will pose a formidable engineering task if one is to design an integrated detector array.

As a practical alternative, we propose a novel approach to achieve unit quantum efficiency and enhance the photoconductive gain, while at the same time keeping the physical length of the detector element small and the dopant concentration low. This objective is accomplished by creating a resonant absorption-cavity internal to the detector element.

Consider a detector element of thickness d and index of refraction n. The faces of this detector, made parallel to within a tight tolerance, constitute the end reflectors of an internal Fabry-Perot etalon. If d is selected so that $d = m\lambda_0/2n$, where m is an integer and λ_0 is a desired vacuum wavelength within the spectral response of the detector, the detector will be resonantly absorptive and the standard relationships governing a lossy Fabry-Perot resonator will apply. Fig. 1 shows the cross sectional diagram of a resonant photoconductor.

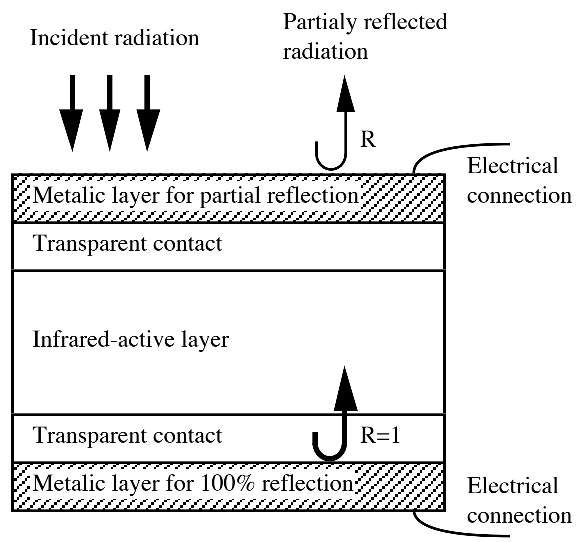

Fig. 1- Typical cross sectional diagram of a resonant photoconductor.

The full treatment of this subject, which included the formulation of the effective absorption coefficient of this resonant detector, has been previously published by the authors.[5] It was derived that at resonance the total fractional power reflected and the total fractional power absorbed by the detector were given respectively by:

$$\frac{I_r}{I_i} = \frac{(\sqrt{R}-A)^2}{(1-A\sqrt{R})^2} \tag{1}$$

$$\frac{I_a}{I_i} = \frac{(1-R)(1-A^2)}{(1-A\sqrt{R})^2} \tag{2}$$

where R is the reflectivity of the front surface of the detector and (1–A) is the absorptivity per single pass. The detector's back surface should by 100% reflective in order to achieve total absorption. Inspection of Equation (2) shows that I_a/I_i can be made equal to unity if we have:

$$R = A^2 \tag{3}$$

Under this condition, I_r/I_i, which is the total fractional power reflected by the detector, is zero. Both R and A can be controlled; R by partially metalizing the front surface, and A by changing the dopant concentration. Fig. 2 is a plot of I_a/I_i for A = 0.95, when the detector absorbs 5% of the incident radiation per single pass.

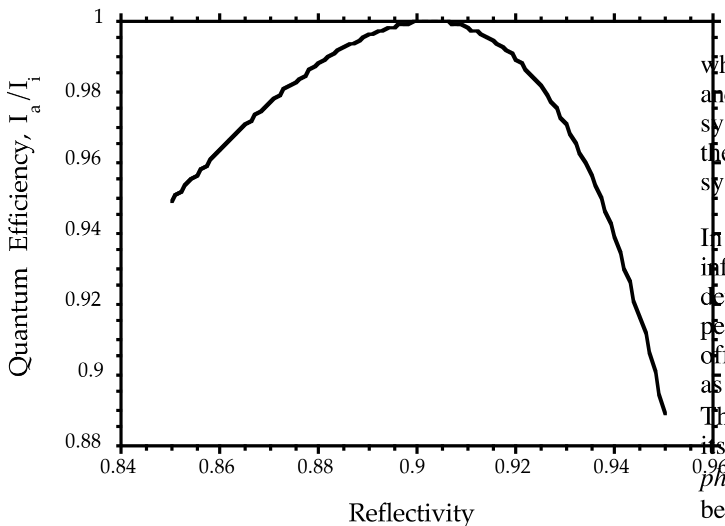

Fig. 2- Total fractional power absorbed by the detector versus front surface reflectivity. Back surface reflectivity = 100%, absorption per pass = 5%.

Since other absorption mechanisms are negligible compared to the photoconductive absorption, I_a/I_i is, in fact, equivalent to the quantum efficiency η. Therefore, once R and A are chosen so that Equation (3) is satisfied, the detector should exhibit unit quantum efficiency at resonant frequencies regardless of its thickness or single-pass absorption. This property will allow us to make the detector very thin, thereby, enhancing the photoconductive gain. The photoconductive gain G, which is defined as the ratio of the number of free carriers passing around the circuit to the number of the photons absorbed, can be written in terms of the mobility μ, the electric field strength E, the carrier lifetime τ, and the interelectrode distance d:[6]

$$G = \frac{\mu E \tau}{d} \tag{4}$$

In a conventional photoconductor, in order to attain high quantum efficiency, the detector thickness must be comparable to its absorption length. For the proposed detector, however, it is no longer necessary to satisfy this criterion since unit quantum efficiency is insured by virtue of the detector's resonant characteristics. It is, therefore, possible to thin the detector to a fraction of its absorption length and use the metalized front and back surfaces as the electrodes for applying the bias field. Using this approach, an order of magnitude increase in the photoconductive gain is easily realizable since, from Equation (4), the photoconductive gain is inversely proportional to the interelectrode distance.

The current responsivity R_i can be substantially improved since it is directly proportional to the quantum efficiency and the photoconductive gain:

$$R_i = \frac{eG\eta}{h\nu} \tag{5}$$

where e is the electronic charge, h is the Plank constant, and ν is the frequency. In an integrated array, where the system is generally amplifier-noise limited, an increase in the detector responsivity is directly translated into lower system NEP.

In summary, we have introduced the concept of a resonant infrared photoconductor and demonstrated that such a detector can, theoretically, exhibit substantially improved performance at selected frequencies. This resonant detector offers many advantages over conventional photoconductors as well as IBC detectors. (i) *Unit quantum efficiency*: The detector is theoretically 100% absorptive regardless of its thickness or single-pass absorption. (ii) *Enhanced photoconductive gain and responsivity*: The detector can be made very thin, which will substantially increase the photoconductive gain and the responsivity. (iii) *Improved noise performance*: Since the detector is opaque, one can conceivably use a material with lower dopant concentration and reduce the NEP. This is an advantage over IBC detectors which require a high purity epi-layer to reduce the NEP to acceptable levels. (iv) *Radiation hardness*: Because the detector element is very thin, it is less susceptible to ionizing radiation.

We are currently in the process of fabricating a Ge:Ga far infrared detector using this approach. A comprehensive characterization of its performance under various conditions will follow.

1- M. D. Petroff and M. G. Staplebroek, US Patent No. 4,568,960 (Feb. 4, 1986).

2- S. B. Stetson, D. B. Reynolds, M. G. Staplebroek, and R. L. Stermer, Proc. SPIE **686**, 48 (1986).

3- D. M. Watson and J. E. Huffman, Appl. Phys. Lett. **52**, 1602 (1988).

4- J. Q. Wang, P. L. Richards, J. W. Beeman, N. M. Haegel, and E. E. Haller, Appl. Opt. **25**, 4127 (1986).

5- J. Farhoomand and R. E. McMurray, Appl. Phys. Lett. **58**, 622 (1991).

6- P. R. Bratt, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic Press, New York, 1977), **12**, p. 55.